Journal of Heat and Mass Transfer Research

Journal homepage: https://jhmtr.semnan.ac.ir

ISSN: 2383-3068

Semnan University

Research Article

Impact of nano-fuel additives and nano-lubricant oil additives on diesel engine performance and emission characteristics

Dipakkumar Chimangiri Gosai [a] *, **Ashishkumar Jashvantlal Modi** [b], **Anil Kumar Gillawat** [b]

[a] *Department of Mechanical Engineering, Shri S'ad Vidya Mandal Institute of Technology, Bharuch, 392002, India*

[b] *Department of Mechanical Engineering, Government Engineering College, Bharuch, 392002, India*

c Department of Mechanical Engineering, Rao Birender Singh State Institute of Engineering & Technology, Rewari, 123411, India

ARTICLE INFO

Article history:

Received: 2024-03-06

Revised:

Accepted:

Keywords:

Diesel Engine;

Nanoparticles;

Fuel/lubricant additives;

Emission characteristics;

Engine performance.

ABSTRACT

Fuel saving and emission control in transportation is a global critical issue so that research requires to concentrate on the energy conservation of diesel engines. Generally, in an internal combustion Engine, around 66 % of the total heat is lost and around 33% is used for Brake Power. It is very important to improve the energy level of the engine in the field of automobiles and that will show from the heat balance sheet of diesel engines. An attempt has been made to fulfil the above requirement by adding CuO and ZnO nano-additives to pure diesel fuel and Al_2O_3 and ZnO nano-lubricant additives to SAE 15W-40 engine lubricant oil by sonication process. Experimental work on vertical twin-cylinder four-stroke, water-cooled advanced computerized diesel engine carried out with no load to full load condition using computerised eddy current dynamometer attachment. The performance of the engine is evaluated by considering specific fuel consumption, brake thermal, mechanical, and volumetric efficiency, and exhaust emission. Results show that Specific fuel consumption is reduced by about 14.98%, Brake thermal efficiency is increased by about 17.62%, and Mechanical efficiency is increased by about 3.94% respectively using both nano fuel additives and nano lubricant additives. For exhaust, the emission is reduced by 20.04%, 10.25% for CO, NOx, and increased in CO_2 by 29.16%. With the application of nano additives in fuel as well as in lubricating oil, the overall thermal performance can be appreciably improved and the exhaust gas pollutant from the engine can be significantly reduced.

1. Introduction

The decline in petroleum reserves and the growing need for energy supplies in recent years have been a subject of discussion among researchers. Diesel engines are essential in developing nations because they have a greater capacity for mileage and are more reliable and durable compared to petrol engines [1, 2]. At present, diesel satisfies around 72% of the need for transportation fuel, while petrol accounts for 23%. The remaining demand is met by alternate fuels like CNG and LPG, which have been experiencing a consistent increase in demand. In 2016, Asia's total primary consumption accounted for 40% of the preceding decade, as reported by the U.S. Energy Information Administration (EIA) [3]. The significant increase

---

* **Corresponding author.**
E-mail address: ashishkumar.modi.mech@gecbhar.gujgov.edu.in

Cite this article as:
Gosai D. C., Modi A. J. Gillawat A. K., 2024. Impact of nano-fuel additives and nano-lubricant oil additives on diesel engine performance and emission characteristics. Journal of Heat and Mass Transfer Research, XX(X), pp. XXXX-XXXX.
https://doi.org/10.22075/JHMTR.2023.39315.2050

in worldwide energy requirements indicates that reliance on oil supplies will continue to expand in the future. Furthermore, the excessive use of petroleum products is also intensifying the accumulation of hazardous contaminants in the environment [4].

Worldwide, air pollution is responsible for the deaths of three million people annually, according to World Health Organization research [5]. The research also demonstrated that the air quality index has been declining due to the rising number of vehicles on the road in recent years. Figure 1 shows some of the factors that are contributing to air pollution as a result of the increased number of vehicles on the road [3]. The research from the International Energy Agency (IEA) states that the only way to tackle the issues of undesirable climate change and our reliance on fossil fuels is for the world to move away from these fuels and towards alternatives [6].

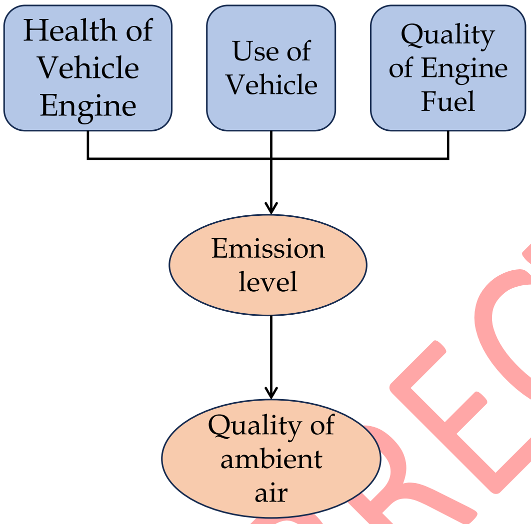


Fig. 1. Factors affecting the quality of ambient air [3]

Various researchers performed experimental and numerical studies to identify different alternatives to fossil fuels which involve various biofuels. The Global Biofuels Alliance was formed at the recently finished G20 meeting in New Delhi hosted by India. It is a project spearheaded by India and aims to bring together governments, international organizations, and business to encourage the use of biofuels [7]. The term "biofuel" refers to hydrocarbons that are made from organic materials using certain processes. The two most common types of biofuels are biodiesel and bioethanol.

Kumar et al. [8] performed an experimental study to investigate diesel engine performance by blending Jatropha methyl ester with tyre pyrolysis oil. They concluded that One of the environmentally favourable ways to generate energy is through the pyrolysis of used tyres. This method has additional benefits, such as producing energy and decreasing reliance on fossil fuels, which in turn lessens the strain of importing crude oil.

To forecast how diesel engines would operate when fed different types of biofuels, a variety of optimization techniques are used. Goga et al. [9] employ Artificial neural network (ANN) modelling to forecast the performance and emission parameters of a biogas-fueled compression ignition engine operating in dual fuel mode, as part of their investigation. With different engine operating loads and flow rates, ANN models are proven to be useful tools for predicting the performance and emission characteristics of biogas-operated dual-fuel diesel engines.

In order to improve combustion efficiency, fuel economy, and pollution reduction, numerous researchers have used 2D and 3D numerical simulations to analyze different engine modification strategies [10]. Modifications to engine designs and other methods for reducing diesel engine pollution were among the technologies documented by Rao and Sharma [11].

In comparison to engine modification techniques, fuel reformulation is easier, less expensive, and more widely used [12]. The combustion efficiency and fuel economy of CI engines are both enhanced by fuel reformulation, which also helps to reduce exhaust pollutants to a certain degree. Engine modifications, on the other hand, necessitate more expensive production and maintenance costs, as well as the replacement of vehicles powered by outdated diesel engines. The engine modification approach is less recommended because of the problems associated with it. Research efforts have largely focused on fuel modification strategies, which aim to make fuel in a way that is both sustainable and capable of ensuring fuel economy in the future [12, 13].

Fuel additives show promise as a solution to the present problem. Blending additives with diesel, gasoline, or other alternative fuels improves the fuel's characteristics. Improving oxidation stability, deposit formation, corrosion resistance during long-term fuel storage, cold flow characteristics, and contamination are all areas where the additives shine. [14, 15]. The fuel additives discussed can be categorised into various groups, including oxygenated additives, nanoparticles-based additives, water, tocopherol additives, and polymer-based additives. Table 1 provides a list of fuel additives along with their respective qualities.

The additives are blended in a minute proportion with the fuel, often ranging from 20 to 500 parts per million (ppm). Nevertheless, microscale additions encounter challenges such as sedimentation, aggregation, and non-uniform size distribution. Thanks to breakthroughs in Nano-sciences, it is now possible to easily create and utilize particles with diameters smaller than 100 nm as additives in the engine. This effectively resolves the aforementioned issues. The utilization of nanoparticles as additives in diesel and biodiesel fuels holds great potential for enhancing their effectiveness in the future [4, 16, 17].

Table 1. List of fuel additives with their qualities

Sr.	Fuel additives	Qualities	Examples
1	Metal/Metal oxide additives	• Work as a catalyst in combustion process • Augment performance • Lowers emission level	Cerium, Zinc, Alumina, oxide, Ferro-fluids etc.
2	Oxygenated additives	• Enhances combustion • process of fuel • Augments performance • parameters i.e., octane number	Alcohols (ethanol, methanol, butanol, propanol, etc.), ethers (Ethyl tert-butyl, methyl tertbutyl, dimethyl, diethyl, etc.)
3	Cetane number improver additives	• Reduces ignition delay • Enhances cetane number	Di-tertiary-butyl peroxide, 2-Ethylhexyl nitrate
4	Ignition booster additives	• Reduces ignition delay • Reduces noise • lowers emission level	alkyl nitrates (e.g., octyl nitrate, hexyl nitrate, and amyl nitrate)
5	Lubrication oil additives	• Augments tribological properties.	Chlorinated paraffins, Sulfurized lard oils, Phosphate esters, Over based calcium sulfonates
6	Antioxidant additives	• Enhances stability of biodiesel • Reduces temperature of engine cylinder during fuel combustion • Lowers NOx emission.	Alkylated phenol, Phenylene diamine,

The incorporation of nano-additives into fuels is accomplished using ultrasonication. Sonication utilizes high-frequency pressure sound waves to scatter the small particles within the base fluid. Figure 2 illustrates the sequential procedure of combining nanoparticles within the base fuel. However, the clustering of nanoparticles within the base fuel can frequently hinder the efficacy and stability of additives. Therefore, in order to resolve these problems, the solution is rendered stable through the utilization of surfactants and dispersants [18, 19].

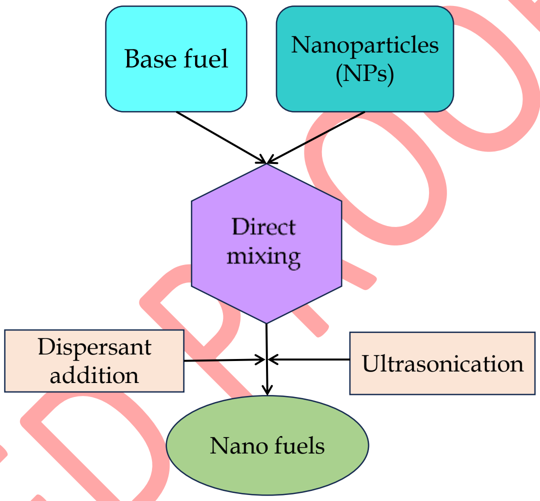


Fig. 2. Nano-fuel preparation

The primary role of the surfactant is to reduce the surface tension between liquids or between a liquid and a solid. The surfactants that are most suitable for blending additives with diesel and biodiesel are ethanol, isopropanol, span 80, and tween 80. Utilizing nanoparticles as an additive for both traditional and non-traditional/alternative fuels is the most promising method for significantly enhancing fuel performance [20, 21].

Nano-additives, which have dimensions in the nanometer range, possess a dense and elevated surface-to-volume ratio in comparison to traditional fluids [22, 23]. Nanoparticles are categorized into five distinct categories based on their constituent elements, properties, and other characteristics as depicted in Figure 3. The thermal conductivity of fluids is a significant factor in influencing the heat transfer capacity. Thermal conductivity plays a role in suspending tiny solid particles in fluids and modifying the fluid's transport characteristics, velocity, and heat transfer characteristics. The thermal conductivity of a base fluid can be improved by adding micrometre or millimetre-sized solid particles with a wide surface area and effective mixing capabilities [24].

Researchers conducted numerical and experimental investigations on the fluid flow and heat transfer properties of several nanofluids comprising SiO$_2$ [25], ZnO [26], CuO [27], Al$_2$O$_3$

[28, 29], and Silver [30] nanoparticles. They evaluated characteristics such as viscosity, thermal conductivity, and the impacts of viscous dissipation. Raei [31] conducted a statistical study to analyse the heat transfer properties of Al_2O_3 – water nanofluid in a counter-flow heat exchanger using the Taguchi technique. He determined that the Nusselt number, which measures heat dissipation, may be enhanced by raising the concentration, flow rate, and temperature of the nanofluid.

Nanoparticles (NPs)

- Metal based NPs
  - Metal / Metal Oxides / Binary oxides
- Carbon based NPs
  - Multi walled carbon nano tubes / Single walled carbon nano tubes / Fullerene
- Nano composites
- Dendrimers
- Quantum dots

Fig. 3. Classification of nanoparticles

Nanofluids exhibit superior stability in comparison to traditional fluids, owing to the size-dependent phenomenon and the random motion of the nanoparticles known as Brownian motion. The nanoparticles' ultrafine form enables unrestricted fluid flow in a microchannel, promoting smoothness. In addition, the utilization of nanofluids allows for the reduction in the size of the heat transfer system, resulting in improved heat transfer performance [32]. Here, the calorific value (CV) of fuel can be enhanced by the increased energy density of the nanoparticles, resulting in greater engine performance.

The nanoparticles function as a catalyst in the combustion process and exert a beneficial influence on ignition parameters. The particles enhance the momentum density, hence increasing the velocity of fuel injection into the combustion chamber and resulting in improved engine performance [22]. The distinctive physicochemical properties, such as magnetic, optical, and electrical features, of nanoparticles have led to their extensive use as fuel catalysts. These catalysts effectively minimize ignition delay, specific fuel consumption (SFC), hazardous emissions, and smoke, while also enhancing the brake thermal efficiency (BTE) of the engine.[17]. The incorporation of nano-powdered metal and metal oxide into the base fuel can improve the characteristics of the fuels [33].

Several researchers have utilized nanoparticles as additives in both diesel and biodiesel to create novel hybrid fuel blends. In their study, Ganesh et al. [34] conducted an experimental analysis to examine the performance characteristics of a diesel engine with a single cylinder. The engine was fueled with Jatropha biodiesel and included the use of magnalium and cobalt oxide nanofuel additives. Due to the reduced calorific value of Jatropha biodiesel, there was a drop in brake thermal efficiency (BTE) and an increase in brake-specific fuel consumption (BSFC). Nevertheless, the inclusion of magnesium and cobalt oxide nanoparticles increases the brake thermal efficiency of the engine by approximately 1% when compared to biodiesel without any additions.

Hosseini et al. [35] investigated the impact of carbon nanotubes as fuel additives on the performance of an engine and the characteristics of its emissions. The engine used in the study was a single-cylinder CI engine. It was noticed that the inclusion of carbon nanotubes reduces engine emissions, specifically unburnt hydrocarbons (UHCs), carbon monoxide, and soot. Furthermore, the engine's performances, such as brake thermal efficiency (BTE) and brake specific fuel consumption (BSFC), were much improved. Hoseini et al. [36] conducted a study where they investigated the use of graphene oxide (GO) nanoparticles as additives in a combination of biodiesel and diesel fuel. The blend was tested on a single-cylinder diesel engine. By employing GO nanoparticles, a decrease of approximately 5% to 22% in Carbon monoxide and a reduction of about 17% to 26% in UHCs were found. Nevertheless, under the same circumstances, there was an observed increase of approximately 7% to 11% in CO2 emissions and a rise of roughly 4% to 9% in NOx emissions.

Ghanbari et al. [37] conduct an experimental study on a six-cylinder diesel engine to examine its performance and emissions when using nano-silver particles (at concentrations of 40, 80, and 120 ppm) and multiwall carbon nanotubes (at concentrations of 40, 80, and 120 ppm) as additives to the diesel fuel. The inclusion of these compounds resulted in a decrease of around 7.08% in brake-specific fuel consumption (BSFC). Furthermore, there was a reported increase of around 2% in engine torque and power when compared to diesel fuel. The researchers noted a significant decrease in the release of unburned hydrocarbon (UHC) and carbon monoxide (CO) when using carbon nanotubes.

Gumus et al. [38] conducted an experimental study on a six-cylinder, direct ignition air-cooled CI engine to investigate the performance characteristics and emission qualities. The engine was fueled with a diesel fuel additive containing silver nanoparticles. By introducing 10 ppm and 20 ppm of silver nanoparticles, the brake-specific fuel consumption (BSFC) decreases by approximately 2% in comparison to regular diesel fuel.

Mehta et al. [39] assessed the efficiency of a diesel engine by including aluminium (Al), iron (Fe), and boron (B) nanoparticles as additives to the diesel fuel. The results showed a decrease of around 7% in Brake Specific Fuel Consumption (BSFC) as compared to diesel fuel without any additives. Kannan et al. [40] conducted an experimental study on a direct-injection diesel engine. They investigated the engine's performance, emissions, and combustion characteristics when fueled with palm biodiesel. In their study, they used ferric chloride ($FeCl_3$) as a fuel-borne catalyst (FBC). It was noted that the addition of $FeCl_3$ resulted in a 6.3% increase in Brake Thermal Efficiency (BTE), while the Brake Specific Fuel Consumption (BSFC) decreased by 8.6%. In addition, a little rise in CO2 emissions resulted in significant decreases in carbon monoxide (CO), nitrogen oxides (NOx), hydrocarbons (HC), and smoke emissions.

Ağbulut [41] examines the impact of nanoparticle size on the performance of a CI engine from both a thermodynamic and economic perspective. The results indicate that the particle size of nanomaterials significantly impacts the performance of internal combustion engines. Smaller particle sizes of nanoparticles of the same type should be prioritized for improved energy, exergy, thermo-economic, exergo-economic, and sustainability outcomes.

Ağbulut et al. [42] investigates the impact of directly adding a high dose of copper oxide (CuO) nanoparticles (<77 nm) to conventional diesel fuel in their further study. Decreases of 14.6% and 20.8% in CO emissions, 6.2% and 13.4% in HC emissions, and 4% and 4.7% in NOx emissions were observed with CuO additions of 1000 and 2000 ppm, respectively. In addition, Ağbulut et al. [43] propose that including metal-oxide based nanoparticles into biodiesel blends yields superior outcomes compared to utilizing biodiesel alone in CI engines.

An investigation into the development and use of surfactant-modified catalytic ceria nanoparticles as fuel additives in a 4-stroke diesel engine powered by biodiesel derived from coconut oil is detailed in the work of Roy et al. [44]. Here, efficiency improved by 5% during the load test, with a 45% drop in hydrocarbon (HC) emissions and a 30% drop in nitrogen oxide (NOx) emissions at higher loads.

A single-cylinder, four-stroke, naturally aspirated compression ignition (CI) diesel engine was the subject of extensive exergetic, and exergo-economic calculations carried out by Karagoz et al. [45]. In their investigation, the test engine was run on a variety of fuels, including diesel, a blend of 90% diesel and 10% waste cooking oil (D90B10), D90B10 with 100 ppm of Al_2O_3 nanoparticles, D90B10 with 100 ppm of TiO_2 nanoparticles, and D90B10 with 100 ppm of SiO_2 nanoparticles. According to the results of the exergy, exergo-economic, and sustainability analyses, Nano fuel outperformed neat diesel fuel and diesel-biodiesel blend. When considering all the analyses, it is concluded that the best test fuel for this study is Nano fuel doped with Al_2O_3.

The study conducted by Siddartha et al. [46] aims to examine the impact of various additives on the performance, combustion, and emission characteristics of diesel engines when used in biodiesel. The researchers determine that the utilization of diverse fuel additives in conjunction with biodiesel aids in diminishing numerous detrimental emissions, hence facilitating the attainment of a sustainable environment and mitigating the unfavorable consequences of global warming, such as climate change.

Hoang et al. [47] presents an exhaustive literature review to demonstrate performance of CI engine with diesel and biodiesel as base fuel and metal nanoparticles as fuel additives. Table 2 provides a summary of the comparison results on how nanoparticles affect the performance and emission characteristics of a compression ignition (CI) engine operating under different situations. In summary, choosing a suitable nano-additive is a highly effective method to improve the characteristics of various alternative fuels and mitigate the negative emissions associated with CI engines.

In CI engines, to decrease consumption of energy and hence lower CO_2 emissions, it is imperative to enhance the energy efficiency of mechanical systems. A significant approach to do this is by developing lubricants that minimize friction in machine components. An effective design strategy involves optimizing the rheology of the liquid lubricant to minimize hydrodynamic shear, churning, and pumping losses. Practically, this typically involves decreasing the thickness of the lubricant to the minimum level that still allows for the presence of fluid or mixed film lubrication.

An alternative method involves incorporating minute amounts of friction modifier additives into the lubricant to decrease friction in the boundary and mixed lubrication conditions. Figure 4 presents a summary of the progress in the development of lubricating additives, as documented by Spikes [48]. The scientific study of friction, lubrication, and wear is referred to as Tribology. The method employed to decrease wear and friction is the field of tribology. The occurrence of machine failure can be attributed to friction and wear, resulting in the wastage of significant energy owing to friction in machine components.

Table 2. Summary of the nanoparticles affecting the performance and emission characteristics of a CI engine

Ref.	Engine type	Base fuel (Diesel / Biodiesel)	Nano-particles	Operating condition	Engine performance		Emission performance			
					BTE	BSFC	CO	HC	NOx	Smoke
Youssef and Ibrahim [49]	1-cylinder 4-stroke, DI	waste cooking oil biodiesel	$ZnAl_2O_4$ (100 ppm)	Different pressure and Load	Rise (2-5%)	Reduce (3%)	-	-	-	-
Yuvarajan et al. [50]	1-cylinder 4-stroke, DI, AC	Must-urd	TiO_2 (100 and 200 ppm)	1100 RPM	-	-	Reduce (8-13%)	Reduce (4.2%)	Reduce	Reduce
Prabakaran and Vijayabalan [51]	1-cylinder 4-stroke, DI, WC	Ethanol + Butanol	ZnO (100, 200 and 300 ppm)	Different pressure and Load	Rise (7.9% for 200 ppm, 10.8% for 300 ppm)	-	Reduce	Reduce (48.5%)	Increase	Reduce (15.6% for 200 ppm, 26.8% for 300 ppm)
Prabu [52]	1-cylinder 4-stroke, DI, AC	Jatropha	Al_2O_3, CeO_2 (30 ppm)	1500 RPM	Rise (3-4%)	Reduce (1-2%)	Reduce (40-50%)	Reduce (33%)	Reduce (13% for Al_2O_3l and 29% for CeO_2)	-
Sajith, Sobhan, and Peterson [53]	1-cylinder 4-stroke, DI, WC	Jatropha	CeO_2 (20-80 ppm)	1500 RPM	Rise (1.5%)	Reduce	Reduce	Reduce (25-40%)	Reduce (30%)	-
Chandrasekaran et al. [54]	1-cylinder 4-stroke, DI, WC	Mahua (B20)	CuO (50 ppm)	1500 RPM	Rise	-	Reduce (15-20%)	Reduce (5-10%)	Increase (2-5%)	Reduce (15-25%)
Prabakaran and Udhoji [51]	1-cylinder 4-stroke, DI	Diesel, Biodiesel, Ethanol	ZnO (250 ppm)	1500 RPM	Rise	Reduce	Reduce	Reduce	Increase	Slight Reduce
Gumus et al. [38]	1-cylinder 4-stroke, DI, WC	Diesel	CuO, Al_2O_3 (50 ppm)	1200 – 3600 RPM	Slight Rise	Reduce	Reduce	Reduce	Reduce	-
Jayanthi and Rao [55]	1-cylinder 4-stroke, DI	Linseed oil	CuO (40, 80 and 120 ppm)	1500 RPM	Rise (3-4%)	Reduce	Reduce	Reduce	Reduce	-
Annamalai et al. [56]	1-cylinder 4-stroke, DI, WC	Lemongrass Oil emulsion oil	CeO_2 (30 ppm)	1500 RPM	Rise (17.2%)	Slight Reduce	Reduce (15.6%)	Reduce (24.8%)	Reduce (6.4%)	-
Devarajan et al. [57]	2-cylinde, DI, WC	Mahua	Magnetite (1% vol)	1300 RPM	Rise (2.27%)	Reduce (5.11%)	Reduce (32.6%)	Reduce (16.7%)	Reduce (9.02%)	Reduce (14.28%)

Table 2. Summary of the nanoparticles affecting the performance and emission characteristics of a CI engine (Conti.)

Ref.	Engine type	Base fuel (Diesel / Biodiesel)	Nano-particles	Operating condition	Engine performance		Emission performance			
					BTE	BSFC	CO	HC	NOx	Smoke
Shaafi and Velraj [58]	1-cylinder 4-stroke, DI, AC	Diesel, Soya-bean, ethanol blend	Al_2O_3	1500 RPM	Rise (17.9%)	Reduce	Reduce	Reduce	Reduce	-
Ozgur et al. [59]	4-cylinder 4-stroke, DI, WC	Rape-seed	MgO (25 and 50 ppm)	1200-1300 RPM	Rise (6.8% for 25 ppm, 4.4% for 50 ppm)	-	Reduce (17.4% for 25 ppm, 16.9% for 50 ppm)	-	Reduce (10.7% for 25 ppm, 16.7% for 50 ppm)	-
Aalam, Saravanan, and Kannan [60]	1-cylinder 4-stroke, DI, WC	Zizipus Jujube	Al_2O_3 (25 and 50 ppm)	1500 RPM	Rise (2.5%)	Reduce (6%)	Reduce	Reduce	Reduce	-
Sadhik and Anand [61]	1-cylinder 4-stroke, DI, AC	Jatropha	Al_2O_3, CNT, Al_2O_3 + CNT (25 and 50 ppm)	1500 RPM	Max. for Al_2O_3 + CNT blend	Reduce	Reduce	Reduce	Minimum for Al_2O_3 + CNT blend	-
Gürü et al. [62]	-	Diesel	MnO_2, MgO, CuO, CaO	-	Rise (0.8%)	Minimum for MnO_2	-	-	Reduce	-
Vellaiyan and Partheeban [63]	1-cylinder 4-stroke, DI	Soya-bean	ZnO (100 ppm)	-	-	-	Reduce (40%)	Reduce (33.3%)	Reduce (41.4%)	Reduce (28.3%)
Agbulut et al. [43]	1-cylinder 4-stroke, DI, AC	Waste cooking oil	TiO_2, SiO_2, Al_2O_3 (100 ppm)	2000 RPM	-	-	Reduce	Reduce	Reduce	Reduce

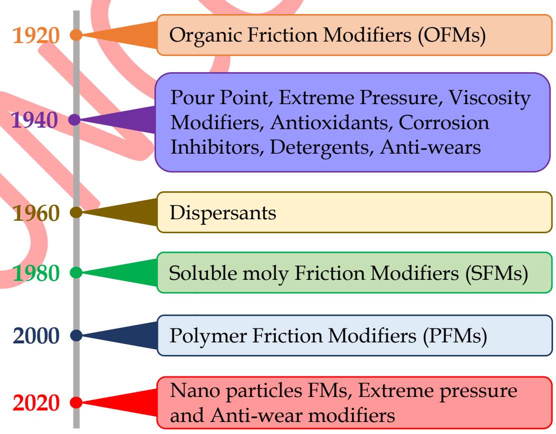


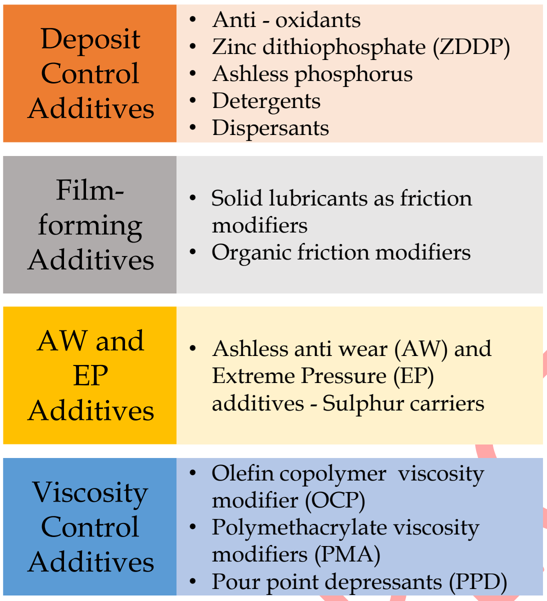
Fig. 4. Timeline summary of development of lubricating additives [48]

To address these problems, the most efficient strategy is to apply lubrication to the machinery. Lubricants are extensively employed in various industries and production facilities to safeguard items and instruments against deterioration and uphold their respective surface structure. In addition, lubricants enhance the coefficient of friction (COF) of manufacturing processes and reduce the buildup of surplus heat in mechanical systems.

Therefore, it is crucial to prioritize the improvement of lubricating oil qualities in order to safeguard machinery from potential problems and reduce energy usage [64]. Base fluids in diesel engines have a vital function of lubricating and creating a barrier between moving surfaces, as well as removing heat, preventing wear, and preventing contamination in the system.

Nevertheless, it is necessary to incorporate appropriate additives into any lubricating oil mixture to improve specific characteristics, such as resistance to oxidation, reduction of friction and wear, protection against corrosion, and stability against biological breakdown.

Another concern is that the base fluid, which acts as a carrier for additives, must have the ability to retain the additives in the solutions under all working circumstances [65]. Approximately 10% by weight of the final lubricant product consists of additive packages. Nevertheless, this can vary considerably, depending on the uses [66]. According to Rudnick [67], the lubricant additives can be classified as illustrated in Figure 5.



Deposit Control Additives	• Anti - oxidants • Zinc dithiophosphate (ZDDP) • Ashless phosphorus • Detergents • Dispersants
Film-forming Additives	• Solid lubricants as friction modifiers • Organic friction modifiers
AW and EP Additives	• Ashless anti wear (AW) and Extreme Pressure (EP) additives - Sulphur carriers
Viscosity Control Additives	• Olefin copolymer viscosity modifier (OCP) • Polymethacrylate viscosity modifiers (PMA) • Pour point depressants (PPD)

Fig. 5. Classification of general lubricant additives utilised in industry

In recent years, there has been a major rise in research on lubricants that incorporate nanoparticles to effectively manage systemic wear and friction. A broad spectrum of research has been conducted on organic and inorganic nanoparticles for their utilization as extreme pressure (EP) and anti-wear agents. Friction researchers explored many perspectives on the adsorption, penetration, and tribo-chemical reaction related to the friction-reducing properties and anti-wear processes of nanoparticles. Research has demonstrated that nanoparticle additives have superior tribological capabilities compared to conventional solid lubricant additives [68-72].

Studies on nanoparticle additives are categorized into metals, metals oxides, non-metals, nano carbon-materials, and Boron-based nanoparticles. Ali et al. [73], Waqas et al. [74], Shahnazar et al. [75] and Srivyas and Charoo [76] were presented an exhaustive review on application of nanoparticles additives in lubricants to improve its tribological properties. Table 3 shows several earlier research works carried out on metal oxide nanoparticles as lubricant additives.

Table 3. Research work carried out on metal oxide nanoparticles as lubricant additives [75]

Reference	**Additives**
Battez et al. [70]	CuO, ZnO, ZrO_2
Wu et al. [77]	CuO, TiO_2
Mangam et al. [78]	Cu, CeO_2
Jia et al. [79]	Al_2O_3, SiO_2
Battez et al. [80]	CuO
Song et al. [81]	$ZnAl_2O_3$
Shi et al. [82]	Al_2O_3

Based on the literature study, it is evident that the majority of researchers investigate the performance of CI engines by incorporating nanoparticle additives into either the base fuel or the lubricants. There is a scarcity of information that investigates the impact of adding nanoparticles to both the base fuel and lubricant. The author is motivated to conduct a study to investigate the performance of CI engines and their emissions by including nanoparticle additions in either the basic fuel or lubricants.

The primary objectives of the present experimental study are as follows:

1. To analyze the performance of a diesel engine by introducing nanoparticle additions into either the basic fuel or the lubricants. In this case, a combination of CuO and ZnO nanoparticles is used as additives for diesel fuel. The lubricating oil additives consist of a combination of Al_2O_3 and ZnO nanoparticles.
2. To assess the performance of the diesel engine by analyzing several engine parameters such as Specific Fuel Consumption (SFC), Brake Thermal Efficiency (BTE), Mechanical Efficiency (ME), Volumetric Efficiency (VE), Noise level, and changes in lubricating oil viscosity.
3. To evaluate the emission performance of a diesel engine by analyzing the exhaust gases for parameters such as smoke density, NOx emission, CO and CO_2 emissions, and Hydrocarbon (HC) emission.

2. Materials and methods

2.1. Preparation of Nanofuel and Nano lubricating oil

The current study used regular diesel as the primary fuel for the compression ignition engine.

According to the engine handbook provided by Kirloskar Oil Engines Limited [83], it is recommended to use SAE 15W-40 engine oil as a lubricant for diesel engines. Additionally, the SAE 15W-40 lubricant is appropriate for use in vehicle diesel engines, particularly those with inter-cooling and turbocharging. The SAE 15W-40 lubricant oil offers wear protection to engine components and effectively minimizes the accumulation of abrasive deposits [84].

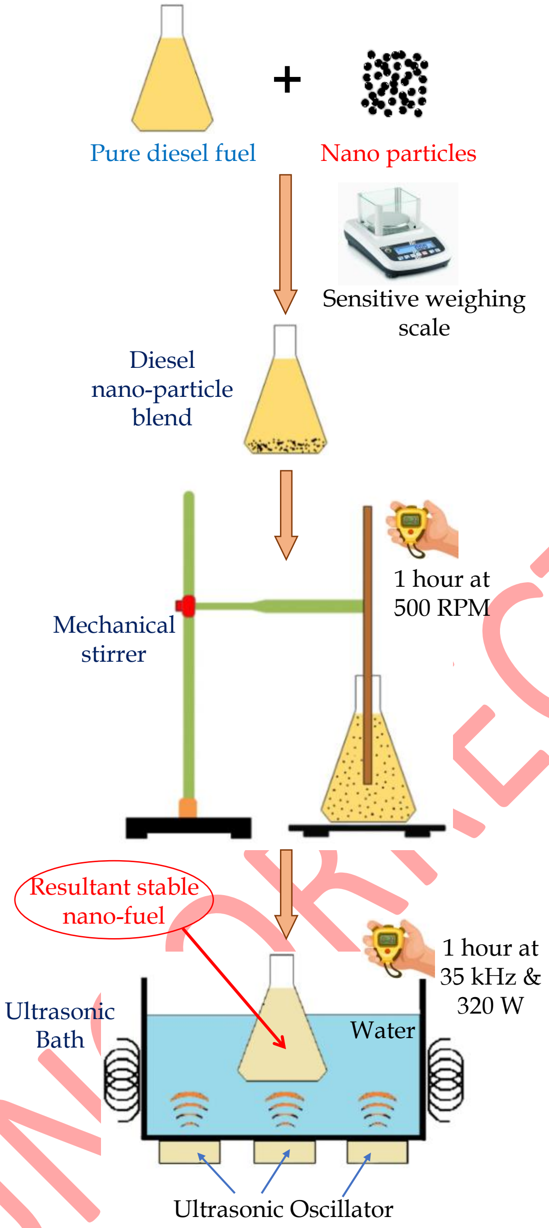


Fig. 6. Steps involved in nano fuel preparation

For the current study, nanoparticles are mixed with base fuel and lubricant oil by sonication process by sonicator equipment available at Ankleshwar Research and Analytical laboratory (ARAIL), Ankleshwar, Gujarat, India.

The steps involved in the preparation of nano fuel are as depicted in Figure 6. Nano particles of different materials are purchased from M/s. Adnano Technologies, Karnataka, India. Table 4 shows various properties of nanoparticles.

Every individual nanoparticle is measured to have a mass fraction of 100 parts per million (ppm). Specifically, a 100mg nanoparticle was added to 1kg of diesel fuel. The suspended nanoparticles mass was measured using Radwag brand precision scales (Model: AS 110.R2 PLUS Analytical Balance) with an accuracy of ± 0.001g. Subsequently, the nano-fuel blend was evenly distributed using a Bandelin Sonorex brand ultrasonic bath (Model: Digitech DT 514 H) [85] operating at a frequency of 35kHz and a power of 320W for a duration of one hour.

A nano fuel blend consisting of diesel fuel mixed with copper oxide (CuO) and zinc oxide (ZnO) nanoparticles was created. The quantity of the blend was 7 liters, as shown in Figure 7 (a).

Fig. 7(a). Pure Diesel and nano fuel blend

The same procedure was utilised to create a mixture of SAE 15W-40 engine oil with nanoparticles of aluminum oxide (Al_2O_3) and zinc oxide (ZnO) to produce lubricant blends. The volume of the mixture was 5 liters, as indicated in Figure 7 (b). The test fuels possessed the main characteristics outlined in Table 5.

Fig. 7(b). SAE 15W-40 lubricant engine oil and lubricant blends

Table 4. Properties of Nanoparticles

Properties	ASTM standards	Al_2O_3	ZnO	CuO
Purity, %	-	99.90	99.90	99.90
Average particle size, nm	D6913	30-50	30-80	30-80
SSA, m^2/g	C1069	110	100-120	60-80
Molecular weight, g/mol	D6474	101.96	81.408	79.545
Molecular formula	-	Al_2O_3	ZnO	CuO
Melting point, °c	D3418	2055	1,975	1,326
Bulk density, g/cm^3	D1895	0.2-0.4	0.69	0.99
Physical form	-	Powder	Powder	Powder
Morphology	-	Spherical	Spherical	Spherical
Colour	-	White	Milky white	Black

Table 5. Properties of conventional Diesel fuel and modified nano fuel

Properties	ASTM standard	Diesel	Nanofuel	Lubricant oil	Nano lubricant oil
Density @ 15 °C, kg/m	D1298	835	847	865	866
Kinematic viscosity @ 40 °C, cSt	D446	2.20	3.20	77	80.8
Kinematic viscosity @ 100 °C, cSt	D446	-	-	18.8	19.7
Flash point, °C	D93	48	59	-	-
Fire point, °C	D93	55	62	-	-
Calorific value, MJ/kg	F976	42.3	43.4	-	-
Viscosity Index (VI)	D2270	-	-	266.71	268
Total base number (mgKO/Hg)	D2896	-	-	2.13	2.04

Table 6. Engine specification

Engine make and type	Kirloskar Diesel Engine (AV2)
Compression ratio (*r*)	16.5
Diameter of piston, mm	80
Stroke length, mm	110
Air: fuel ratio	14.8:1
Rated power, HP	10
Engine speed, RPM	1500
Compression pressure, bar	60
Direction of rotation	Clockwise

2.2. Experimental Setup

Table 6 displays the comprehensive parameters of a two-cylinder vertical, four stroke, single acting, high-speed, water-cooled compression ignition engine. The centrifugal governor controlled the velocity of the engine.

The engine was linked to a computerized electrical dynamometer in order to quantify the power generated. The engine was equipped with instruments to measure parameters such as fuel consumption, engine load and speed, cooling water temperature, inlet air temperature, exhaust gas temperature, and smoke density. The experimental setup is depicted schematically and pictorially in Figures 8 and 9. The engine was tested from no load to maximum load circumstances while maintaining a constant speed of 1500 rpm and varying the load. The measurements of several parameters were documented at every stage of the operation.

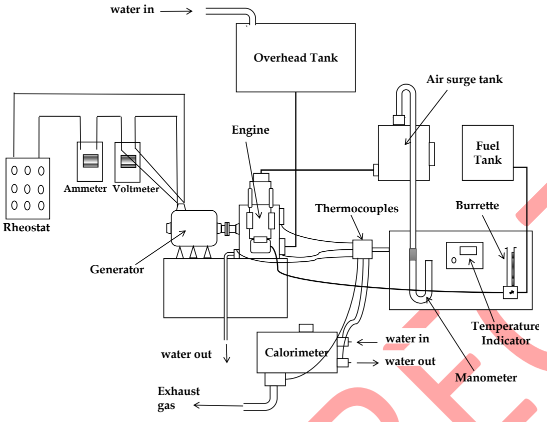


Fig. 8. Schematic diagram of the experimental set up

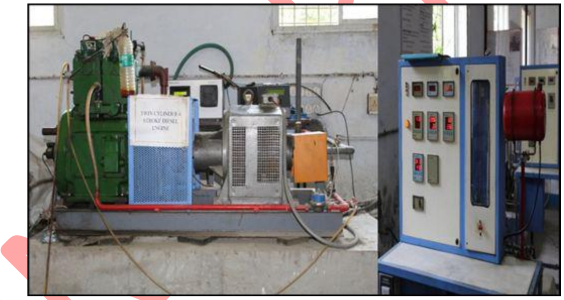


Fig. 9. Pictorial diagram of the experimental set up

The following cases were tested in an experimental setup: (1) a base engine with pure conventional diesel and SAE 15W-40 engine lubricant oil; (2) a modified nano lubricant oil and pure conventional diesel; and (3) a modified nano fuel and modified nano lubricant oil.

At each operating point, the engine's specific fuel consumption, brake thermal efficiency, mechanical efficiency, volumetric efficiency, noise level, lubricant viscosity, and exhaust gases were measured. It was also necessary to wait for the engine to stabilize before recording the dynamometer load, speed, fuel, and air flow under each running condition. Table 7 displays the associated uncertainty in the computed characteristics with regard to the measured parameter.

Table 7. Measured uncertainties in engine performance parameters.

Parameter	Uncertainty
Engine speed, RPM	±1%
Engine cooling water temperature, °c	±0.2°c
Engine oil temperature, °c	±0.2°c
Specific fuel consumption, g/kWh	±1%
Effective efficiency, %	±0.5%

3. Results and discussion

3.1. Specific Fuel Consumption (SFC)

Specific fuel consumption is a criterion used to assess the performance of engines of different sizes. This is the correlation between the rate of fuel consumption and the amount of energy produced by the engine. High fuel consumption in the engine indicates a greater need for fuel to generate power, resulting in less efficiency. Figure 10 illustrates the relationship between specific fuel consumption (SFC) and changes in brake power. It has been noted that the specific fuel consumption (SFC) reduces to its lowest value as the brake power increases up to the optimal loading state, and then slightly increases in overload situations.

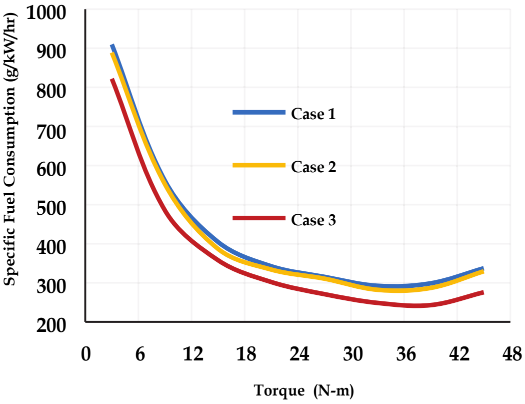


Fig. 10 Variation in SFC with respect to Brake power

Case-2 demonstrates a decrease in fuel consumption while utilizing a modified nano lubrication oil in combination with pure diesel base fuel, while Case-3 exhibits an even greater reduction in fuel consumption by utilizing a modified nano fuel with the modified nano lubricant oil. This performance behavior is attributed to the reduction of heat loss and the achievement of total combustion in the chamber.

Under optimum load conditions, the specific fuel consumption for Case-3 is around 248 g/kW-hr. Case-3 shows a decrease in SFC of approximately 14.98% compared to Case-1, and a decrease of approximately 11.91% compared to Case-2.

3.2. Brake Thermal Efficiency (%)

The brake power and calorific value of fuel are utilized to determine brake thermal efficiency (BTE). The inverse of specific fuel consumption is Brake thermal efficiency. Figure 11 demonstrates that the BTE (Brake Thermal Efficiency) of all the fuels examined is inferior to that of diesel fuel. The brake's thermal performance improves as the loads grow.

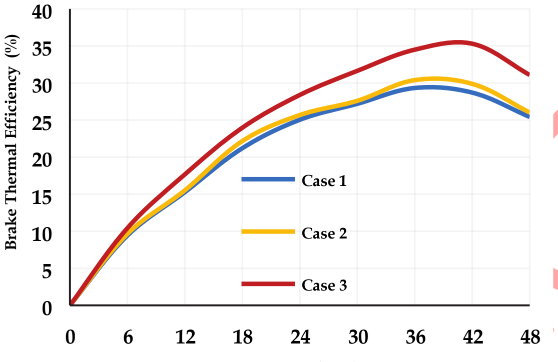


Fig. 11. Variation in BTE with respect to engine torque.

Figure 11 demonstrates that Case-2 and Case-3 display an improved Brake Thermal Efficiency (BTE) in comparison to Case-1, which represents the standard engine without nano additions. The utilization of nano-lubricants (Al_2O_3+ZnO) in SAE 15W-40 engine lubricant oil with diesel enhances brake thermal efficiency. This efficiency is further elevated by the combined use of both nano-fuel and nano lubricant oil.

Under the rated power conditions, the brake thermal efficiency for Case-1 is 29.33%. Based on the data, it can be noticed that Case-3 shows the biggest improvement in BTE, with an enhancement of approximately 34.50%. In comparison, Case-2 exhibits an increase in BTE of up to 30.39%. The increase in thermal braking efficiency of the diesel mixture can be attributed to its higher energy content and calorific value in comparison to diesel. As a consequence, this leads to increased breakdown, thorough combustion, and elevated heat generation.

3.3. Mechanical Efficiency (%)

Based on the data presented in Figure 12, it can be noticed that the mechanical efficiency (ME) improves as the load condition, specifically engine torque, increases. The highest mechanical efficiency is obtained in Case-3. It has been observed that the mechanical efficiency (ME) of Case-2 and Case-3 is consistently higher than that of Case-1, which is the base engine, for all levels of engine torque. The improvement in lubricant oil characteristics is due to the inclusion of nanoparticles (Al_2O_3+ZnO) as a lubricant additive. Additionally, this reduces the frictional power of the diesel engine.

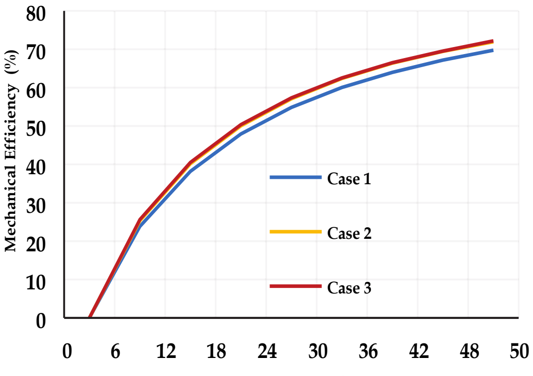


Fig. 12. Variation in ME with respect to engine torque.

The mechanical efficiency of the Case-1, the standard engine without nano additions is 63.98% at optimal load conditions. The addition of nano compounds can increase mechanical efficiency to 66.38% for Case 3 and 66.50% for Case 2.

3.4. Volumetric Efficiency (%)

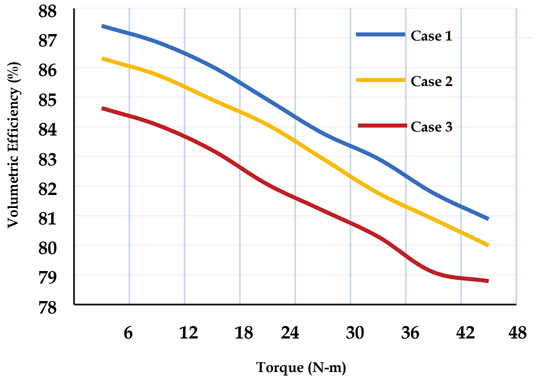


Fig. 13. Variation in VE with respect to engine torque.

The base engine (Case-1) achieves a maximum volumetric efficiency (VE) of 82.92% under the rated condition. The incorporation of nano additives in fuel and lubricants, along with the achievement of complete combustion in the chamber, leads to a decrease in volumetric efficiency. Specifically, in Case-2, the reduction is 1.40%, while in Case-3, it is 3.18%, as compared to Case-1. This information is visually shown in Figure 13. In this case, the full combustion process shows an increase in both peak pressure and exhaust pressure, leading to a decrease in the amount of air taken in. Therefore, a significant decrease in VE is noticed during the process.

3.5. Noise level

The noise level for the base engine (Case-1) was measured to be between 91.7 dB and 93.5 dB under optimal load conditions. According to Figure 14, the addition of nano-lubricant additives and nano-fuel additives leads to an increase in noise level.

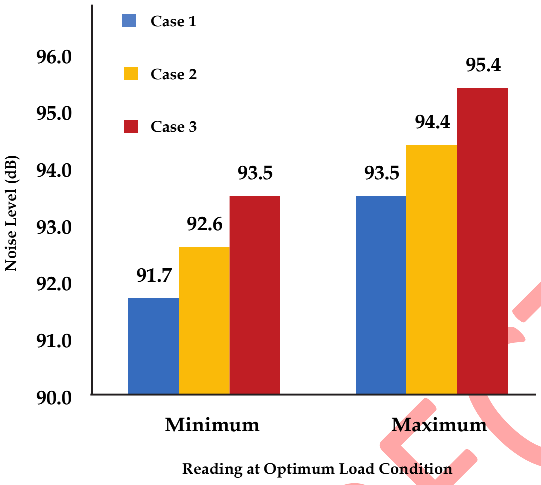


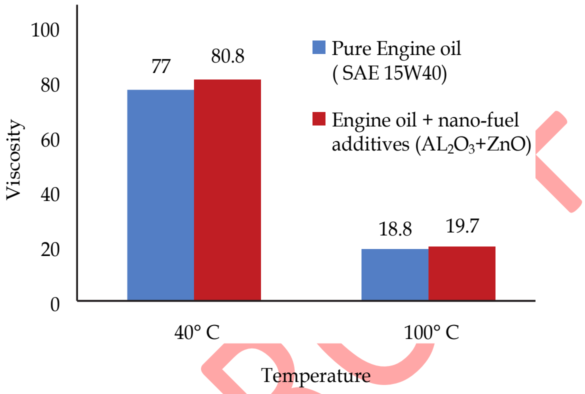
Fig. 14. Noise level at rated torque conditions

By incorporating nanoparticles into the base fuel and lubricating oil, it has been noticed that the noise levels for all the different scenarios are consistently below the acceptable threshold, even under normal operating conditions.

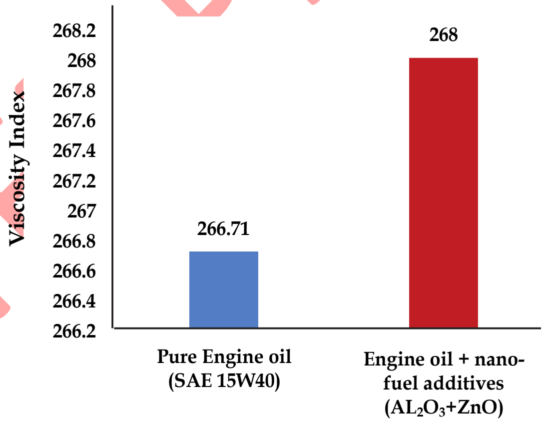
3.6. Variation in lubricant oil viscosity

The properties of oil viscosity and residue in SAE 15W-40 engine lubricant oil and modified nano lubricants (containing Al_2O_3 and ZnO nano particles) were analyzed at Ankleshwar Research & Analytical Laboratory (ARAIL) in Ankleshwar, Bharuch, India. This analysis was conducted using a Capillary U-Tube Viscometer according to ASTM D446 standards [86].

Figure 15(a) demonstrates that the viscosity of SAE 15W-40 engine lubricant oil at 40°C and 100°C is lower when compared to the viscosity of modified nano-lubricant oil obtained by blending base engine oil with nanoparticle additives. Higher viscosity indicates a lubricant oil that is stable and aids in the formation of a reliable lubricating layer between engine components, especially at varying temperatures. The presence of a nanoparticle between the oil layers facilitates smooth and effortless motion between the nano-lubricant oil, reducing the amount of viscous friction.



(a) Lubricating oil viscosity with rise in temperature



(b) Viscosity index

Fig. 15. Variation viscosity of lubricating oil

Furthermore, Figure 15(b) illustrates the viscosity index of both SAE 15W-40 engine lubricant oil and modified nano-lubricant oil. The viscosity index of the modified nano-lubricant oil is found to be 0.484% more than that of the SAE 15W-40 engine lubricant oil. The addition of Al_2O_3 and ZnO nanoparticles to SAE 15W-40 engine lubricant oil results in an increase in the viscosity index. This increase signifies a more consistent viscosity when subjected to changes in temperature. Nevertheless, it has been noted that an increase in resistance to thinning of the lubricating oil layer leads to improved fuel economy.

3.7. Heat Balance Sheet

A heat balance sheet is created for a twin-cylinder 4-stroke diesel engine to account for the heat supplied by fuel (HS), the heat equivalent to brake power (H. BP), the heat carried by cooling water jackets (H. CW), the heat carried by exhaust gas (H. EX), and the heat lost by radiation and unaccounted losses (H. UC).

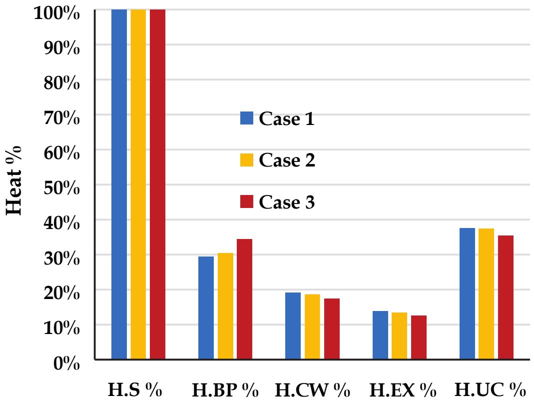


Fig. 16. Heat balance sheet

Figure 16 shows that the base engine for Case-1 uses 29.42% of its heat for brake power. This rises to 30.39% for Case-2 when nano-lubricant is added, and it goes up to 34.50% for Case-3 when nano-fuel is added as well.

Figure 16 demonstrated that the amount of heat used to produce brake power (H. BP) goes up when the amount of heat lost in jacket cooling water (H. CW) and exhaust gases (H. Ex) goes down. The amount of heat unaccounted (H. UC) is also lowered from 37.5% to 35.48%.

3.8. Exhaust gas analysis

3.8.1. Smoke Density

Figure 16 shows how the density of the smoke changes when the engine power is changed in terms of engine torque. One way to measure the amount of smoke released is by its opacity. A diesel car releases a lot of smoke. Poor repair or motors that don't work right can sometimes make smoke worse. The test findings are contingent upon the level of obscurity and the age of the diesel engine.

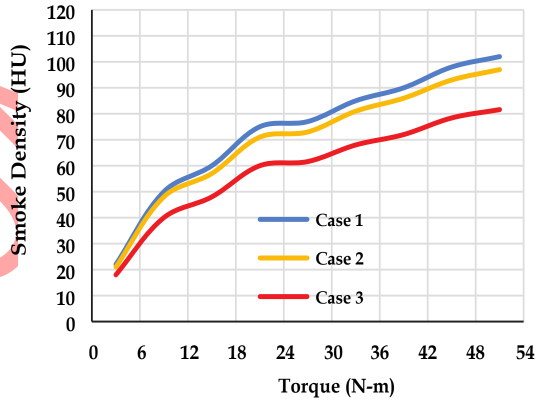


Fig. 17. Variation in smoke density with respect to engine torque

Figure 17 shows that the smoke density of Case-2 decreased by 4.44% and Case-3 decreased by 20% compared to Case-1 of the diesel engine without any nano additives. The decrease in smoke density indicates that the inclusion of nano-fuel additives and nano-lubricant additives promotes a more thorough combustion process.

Furthermore, it has been noted that when the engine torque increases, there is a significant increase in smoke density. This phenomenon can be attributed to the overall abundance of fuel in the air mixture. The amount of smoke produced is influenced by factors such as temperature, duration of the diffusion combustion phase, and reduced oxygen levels. This could be attributed to the process of fuel atomization and the resulting incomplete combustion.

3.8.2. NOx emission

Figure 18 illustrates the variation in NOx emissions as the engine power is adjusted in relation to engine torque. Nitrogen dioxide and nitric oxide are often referred to as nitrogen oxides (NOx). Nitrogen oxides are gaseous compounds that undergo chemical reactions to produce smoke and acid rain. They also play a crucial role in the creation of particulate matter (PM) and ground-level ozone, both of which are linked to negative health impacts. NOx emissions are increased by an excessive load on CI engine.

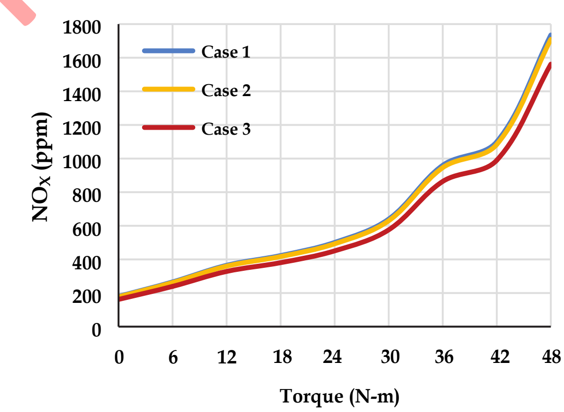


Fig. 18. Variation in NOx emission with respect to engine torque

According to Figure 16, Case-2 and Case-3 show a decrease of approximately 1.46% and 10.25% in NOx emissions compared to Case-1 of the diesel engine without any nano additions, respectively. This result is attributed to the chemical reaction between diesel fuel and CuO nanoparticles mixed with the base fuel as nano-fuel additives.

3.8.3. CO emission

Carbon monoxide (CO) is a combustible gas. It has no color, smell, or taste, and it is slightly more dense than air. Increase in engine loads will raise the CO emissions. If combustion is incomplete, it may cause more emission pollution. If burning isn't finished, it may cause more pollution. This might be because the pre-mixture didn't burn quickly and the diesel mixture had a high viscosity, which caused the droplet volume to rise and the mixture to not dissolve well.

Figure 19 illustrates the relationship between carbon monoxide (CO) emission and engine torque. The incorporation of ZnO as nano additives in modified nano-fuel enhances the engine combustion process. Consequently, there is a noticeable decrease in CO emissions. Case-2 shows a reduction of 4.96% in CO emissions compared to Case-1, while Case-3 demonstrates a reduction of 20.04%.

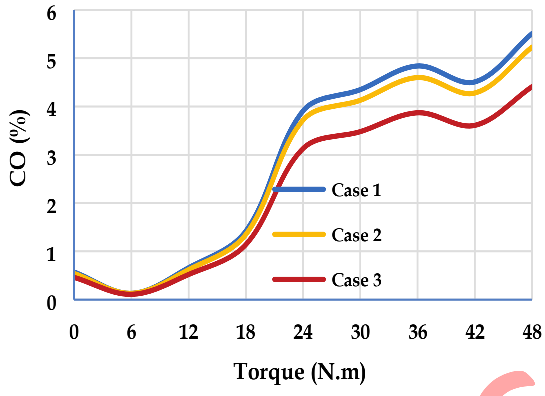


Fig. 19. Variation in CO emission with respect to engine torque

3.8.4. CO_2 emission

Carbon dioxide is a chemical molecular structure composed of a single carbon atom and two oxygen atoms. Carbon dioxide (CO_2) exists in small amounts in the Earth's atmosphere and functions as a greenhouse gas. In a solid state, it is referred to as dry ice. It plays a crucial role in the carbon cycle.

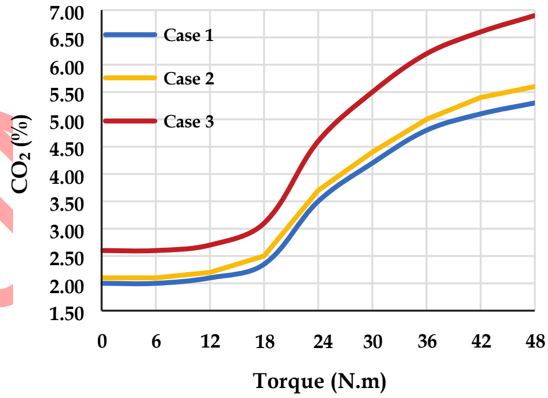


Fig. 20. Variation in CO_2 emission with respect to engine torque

Here, Figure 20 illustrates the relationship between carbon dioxide (CO_2) emission and engine torque. It is observed that emission of CO_2 is increased in exhaust gas by using both modified nano-fuel and nano-lubricants additives with diesel. The highest increase of 29.16% is recorded in Case-3 compared to Case-1, which did not involve any nano additions. Furthermore, there is an observed rise of approximately 4% in Case-2 compared to Case-1.

3.8.5. Hydrocarbon (HC) emission

Figure 21 illustrates the correlation between the emission of hydrocarbons (HC) and the torque produced by the engine. A hydrocarbon is a kind of organic substance composed of atoms of hydrogen and carbon. Hydrocarbons are organic chemicals that serve as the fundamental components of crude oil, natural gas, coal, and other significant sources of energy.

The levels of hydrocarbon rise as development advances. The elevated levels of hydrocarbons (HC) might be attributed to inadequate dissolving of the diesel mixture, which can be attributed to its high viscosity, high density, and low volatility.

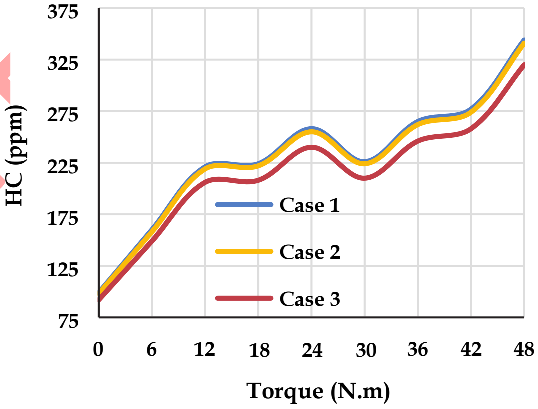


Fig. 21. Variation in HC emission with respect to engine torque

Figure 21 demonstrates that the addition of nano-fuels additives and nano-lubricants additives leads to a significant decrease in hydrocarbon emissions in exhaust gas, indicating a complete combustion process.

It is observed that Case-2 shows a reduction of 1.15% in HC emissions compared to Case-1, whereas Case-3 demonstrates a larger reduction of 7.17%.

4. Conclusion

From the current experimental work, it is concluded that thermal efficiency can be enhanced by adding CuO and ZnO nanoparticles in fuel (conventional diesel) as nano-fuel additives and Al_2O_3 and ZnO nanoparticles in engine lubricant (SAE 15W-40 engine lubricant oil) as nano-lubricant additives, respectively.

Reduction in NOx, CO, unburnt HC and Smoke density in the exhaust are observed whereas CO_2 emission increases which clearly indicates complete combustion in diesel engine.

The engine performance is compared for three different cases – (1) a base engine with pure conventional diesel and SAE 15W-40 engine lubricant oil; (2) a modified nano lubricant oil and pure conventional diesel; and (3) a modified nano fuel and modified nano lubricant oil. After analyzing the experimental outcomes, it can be concluded that:

1. A reduction of about 11.91% in specific fuel consumption (SFC) is shown when only modified nano lubricants are utilized (in Case-2), compared to Case-1 where no nano additives are utilized. Whereas about 14.98% reduction is noted with addition of nano particles in both fuel and lubricants in Case-3 as compared to Case-1. Here, application of nano particles as additives in both fuel and lubricant can significantly reduce the specific fuel consumption. The addition of nano-fuel additives and nano-lubricant additives to diesel fuel and lubricant oil, respectively, increases the brake thermal efficiency by 17.62% in Case-3. In comparison, the blend of pure diesel and lubricant oil with nano-lubricant additives in Case-2 increases the efficiency by 3.61% compared to the basic engine without additives.
2. The mechanical efficiency of diesel engine is raised by an average of approximately 3.94% in both modified cases.
3. The viscosity index of the modified nano-lubricant oil is around 0.484% higher compared to the basic SAE 15W-40 engine lubricant oil. This implies that the viscosity property of the blend remains more stable as the temperature increases.
4. The noise level for all load conditions is well within the permissible limit.
5. The addition of nano-fuel additives to diesel fuel and nano-lubricating additives to lubricant oil enhanced combustion by reducing the density of smoke, as well as the emissions of nitrogen oxides (NOx), carbon monoxide (CO), and hydrocarbons (HC). The addition of nano-fuels and nano-lubricants to the basic fuel results in an increase in CO_2 emissions in exhaust gases, indicating that the combustion process is moving towards a complete combustion. By incorporating fuel and lubricant additives into diesel engines, it is possible to enhance engine performance by reducing fuel consumption and minimizing exhaust gas emissions.

Acknowledgments

The authors would like to acknowledge Mr. Kaushal S. Shah, PG Scholar, Department of Mechanical Engineering, Shri S'ad Vidya Mandal Institute of Technology, Bharuch, Gujarat, India for his support in taking observation in the experimental work.

Funding Statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

References

[1] Casanave, D., J.-L. Duplan, E. Freund, 2007. Diesel fuels from biomass. Pure and Applied Chemistry, **79**(11): pp. 2071-2081 doi: 10.1351/pac200779112071.

[2] Lloyd, A.C.,T.A. Cackette, 2001. Diesel engines: environmental impact and control. Journal of the Air & Waste Management Association, **51**(6): pp. 809-847 doi: 10.1080/10473289.2001.10464315.

[3] Tomar, M.,N. Kumar, 2020. Influence of nanoadditives on the performance and emission characteristics of a CI engine fuelled with diesel, biodiesel, and blends–a review. Energy sources, part A: Recovery, utilization, and environmental effects, **42**(23): pp. 2944-2961 doi: 10.1080/15567036.2019.1623347.

[4] Shaafi, T., K. Sairam, A. Gopinath, G. Kumaresan, R. Velraj, 2015. Effect of dispersion of various nanoadditives on the performance and emission characteristics of a CI engine fuelled with diesel, biodiesel and blends—a review. Renewable and Sustainable Energy Reviews, **49**: pp. 563-573 doi: 10.1016/j.rser.2015.04.086.

[5] WHO, 2016. Ambient air pollution: A global assessment of exposure and burden of disease. W.H. Organization.

[6] World Energy Outlook 2023 Free Dataset. March 2024, International Energy Agency (IEA).

[7] Shine, I., 2023. The Global Biofuel Alliance has just launched, but what exactly are biofuels? W.E. Forum.

[8] Kumar, R., A.S. Yadav, A. Sharma, U. Rajak, T.N. Verma, T. Alam, N. Tiwari, C. Jawahar, 2023. Experimental analysis of a diesel engine run on non-conventional fuel blend at different preheating temperatures.

Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering: pp. 09544089231190754 doi: 10.1177/0954408923119075.

[9] Goga, G., S.K. Mahla, B.S. Chauhan, A.S. Yadav, S. Chakroborty, J. Garg, S.B. Garg, 2023. Predication of performance and emissions characteristics adual fuel engine energized with liquid and gaseous materials by Artificial neural network. Materials Today: Proceedings, doi: 10.1016/j.matpr.2023.01.315.

[10] Kumar, P., A. Darsigunta, B.C. Mouli, V.K. Sharma, N. Sharma, A.S. Yadav, 2021. Analysis of intake swirl in a compression ignition engine at different intake valve lifts. Materials Today: Proceedings, **47**: pp. 2869-2874 doi: 10.1016/j.matpr.2021.03.663.

[11] Rao, G.A.P.,T.K. Sharma, 2020. Engine Emission Control Technologies: Design Modifications and Pollution Mitigation Techniques. Apple Academic Press. doi: 10.1201/9780429322228.

[12] Ying, W., Z. Longbao, W. Hewu, 2006. Diesel emission improvements by the use of oxygenated DME/diesel blend fuels. Atmospheric Environment, **40**(13): pp. 2313-2320 doi: 10.1016/j.atmosenv.2005.12.016.

[13] Song, J., K. Cheenkachorn, J. Wang, J. Perez, A.L. Boehman, P.J. Young, F.J. Waller, 2002. Effect of oxygenated fuel on combustion and emissions in a light-duty turbo diesel engine. Energy & fuels, **16**(2): pp. 294-301 doi: 10.1021/ef010167t.

[14] Hosseinzadeh-Bandbafha, H., M. Tabatabaei, M. Aghbashlo, M. Khanali, A. Demirbas, 2018. A comprehensive review on the environmental impacts of diesel/biodiesel additives. Energy Conversion and Management, **174**: pp. 579-614 doi: 10.1016/j.enconman.2018.08.050.

[15] Shah, P.R.,A. Ganesh, 2016. A comparative study on influence of fuel additives with edible and non-edible vegetable oil based on fuel characterization and engine characteristics of diesel engine. Applied thermal engineering, **102**: pp. 800-812 doi: 10.1016/j.applthermaleng.2016.03.128.

[16] Saxena, V., N. Kumar, V.K. Saxena, 2017. A comprehensive review on combustion and stability aspects of metal nanoparticles and its additive effect on diesel and biodiesel fuelled CI engine. Renewable and Sustainable Energy Reviews, **70**: pp. 563-588 doi: 10.1016/j.rser.2016.11.067.

[17] Kumar, S., P. Dinesha, I. Bran, 2017. Experimental investigation of the effects of nanoparticles as an additive in diesel and biodiesel fuelled engines: a review. Biofuels, doi: 10.1080/17597269.2017.1332294.

[18] Fuskele, V.,R. Sarviya, 2017. Recent developments in nanoparticles synthesis, preparation and stability of nanofluids. Materials Today: Proceedings, **4**(2): pp. 4049-4060 doi: 10.1016/j.matpr.2017.02.307.

[19] Paramashivaiah, B.,C. Rajashekhar. Studies on effect of various surfactants on stable dispersion of graphene nano particles in simarouba biodiesel. in IOP conference series: materials science and engineering. 2016. IOP Publishing.

[20] Soukht Saraee, H., S. Jafarmadar, H. Taghavifar, S. Ashrafi, 2015. Reduction of emissions and fuel consumption in a compression ignition engine using nanoparticles. International journal of environmental science and technology, **12**: pp. 2245-2252 doi: 10.1007/s13762-015-0759-4.

[21] Soni, G.S., P.P. Rathod, J.J. Goswami, 2015. Performance and emission characteristics of CI engine using diesel and biodiesel blends with nanoparticles as additive-A review study. International Journal of Engineering Development and Research, **3**(4): pp. 879-884

[22] Gupta, H., G. Agrawal, J. Mathur, 2012. An overview of Nanofluids: A new media towards green environment. International Journal of environmental sciences, **3**(1): pp. 433-440 doi: 10.6088/ijes.2012030131042.

[23] Senthilraja, S., M. Karthikeyan, R. Gangadevi, 2010. Nanofluid applications in future automobiles: comprehensive review of existing data. Nano-Micro Letters, **2**: pp. 306-310 doi: 10.1007/BF03353859.

[24] Zhu, D., X. Li, N. Wang, X. Wang, J. Gao, H. Li, 2009. Dispersion behavior and thermal conductivity characteristics of Al2O3–H2O nanofluids. Current Applied Physics, **9**(1): pp. 131-139 doi: 10.1016/j.cap.2007.12.008.

[25] Moravej, M., A. Noghrehabadi, A. Esmaeilinasab, E. Khajehpour, 2020. The effect of SiO2 nanoparticle on the performance of photovoltaic thermal system: Experimental and Theoretical approach. Journal of Heat and Mass Transfer Research, **7**(1): pp. 11-24 doi: 10.22075/JHMTR.2020.18904.1254.

[26] Parvar, M., S. Saedodin, S.H. Rostamian, 2020. Experimental study on the thermal conductivity and viscosity of transformer oil-based nanofluid containing ZnO nanoparticles. Journal of Heat and Mass Transfer Research, **7**(1): pp. 77-84 doi: 10.22075/JHMTR.2020.19303.1267.

[27] Aminian, M.R., A.R. Miroliaei, B. Mirzaei Ziapour, 2019. Numerical study of flow and heat transfer characteristics of CuO/H2O nanofluid within a mini tube. Journal of Heat and Mass Transfer Research, **6**(1): pp. 11-20 doi: 10.22075/JHMTR.2018.14156.1205.

[28] Barik, A.K.,B. Nayak, 2017. Fluid flow and heat transfer characteristics in a curved rectangular duct using Al2O3-water nanofluid. Journal of Heat and Mass Transfer Research, **4**(2): pp. 103-115 doi: 10.22075/JHMTR.2017.1689.1115.

[29] Mollamahdi, M., M. Abbaszadeh, G.A. Sheikhzadeh, 2016. Flow field and heat transfer in a channel with a permeable wall filled with Al2O3-Cu/water micropolar hybrid nanofluid, effects of chemical reaction and magnetic field. Journal of Heat and Mass Transfer Research, **3**(2): pp. 101-114 doi: 10.22075/JHMTR.2016.447.

[30] Nath, G., 2018. Physico-Acoustic Study on Thermal Conductivity of Silver Nanofluid. Journal of Heat and Mass Transfer Research, **5**(2): pp. 105-110 doi: 10.22075/JHMTR.2018.12036.1175.

[31] Raei, B., 2021. Statistical analysis of nanofluid heat transfer in a heat exchanger using Taguchi method. Journal of heat and mass transfer research, **8**(1): pp. 29-38 doi: 10.22075/JHMTR.2020.20678.1287.

[32] Basu, S.,A. Miglani, 2016. Combustion and heat transfer characteristics of nanofluid fuel droplets: A short review. International Journal of Heat and Mass Transfer, **96**: pp. 482-503 doi: 10.1016/j.ijheatmasstransfer.2016.01.053.

[33] Nanthagopal, K., B. Ashok, A. Tamilarasu, A. Johny, A. Mohan, 2017. Influence on the effect of zinc oxide and titanium dioxide nanoparticles as an additive with Calophyllum inophyllum methyl ester in a CI engine. Energy Conversion and Management, **146**: pp. 8-19 doi: 10.1016/j.enconman.2017.05.021.

[34] Ganesh, D.,G. Gowrishankar. Effect of nano-fuel additive on emission reduction in a biodiesel fuelled CI engine. in 2011 International conference on electrical and control engineering. 2011. IEEE.

[35] Hosseini, S.H., A. Taghizadeh-Alisaraei, B. Ghobadian, A. Abbaszadeh-Mayvan, 2017. Performance and emission characteristics of a CI engine fuelled with carbon nanotubes and diesel-biodiesel blends. Renewable energy, **111**: pp. 201-213 doi: 10.1016/j.renene.2017.04.013.

[36] Hoseini, S., G. Najafi, B. Ghobadian, M. Ebadi, R. Mamat, T. Yusaf, 2020. Performance and emission characteristics of a CI engine using graphene oxide (GO) nano-particles additives in biodiesel-diesel blends. Renewable Energy, **145**: pp. 458-465 doi: 10.1016/j.renene.2019.06.006.

[37] Ghanbari, M., G. Najafi, B. Ghobadian, T. Yusaf, A. Carlucci, M.K.D. Kiani, 2017. Performance and emission characteristics of a CI engine using nano particles additives in biodiesel-diesel blends and modeling with GP approach. Fuel, **202**: pp. 699-716 doi: 10.1016/j.fuel.2017.04.117.

[38] Gumus, S., H. Ozcan, M. Ozbey, B. Topaloglu, 2016. Aluminum oxide and copper oxide nanodiesel fuel properties and usage in a compression ignition engine. Fuel, **163**: pp. 80-87 doi: 10.1016/j.fuel.2015.09.048.

[39] Mehta, R.N., M. Chakraborty, P.A. Parikh, 2014. Nanofuels: Combustion, engine performance and emissions. Fuel, **120**: pp. 91-97 doi: 10.1016/j.fuel.2013.12.008.

[40] Kannan, G., R. Karvembu, R. Anand, 2011. Effect of metal based additive on performance emission and combustion characteristics of diesel engine fuelled with biodiesel. Applied energy, **88**(11): pp. 3694-3703 doi: 10.1016/j.apenergy.2011.04.043.

[41] Ağbulut, Ü., 2022. Understanding the role of nanoparticle size on energy, exergy, thermoeconomic, exergoeconomic, and sustainability analyses of an IC engine: A thermodynamic approach. Fuel Processing Technology, **225**: pp. 107060 doi: 10.1016/j.fuproc.2021.107060.

[42] Ağbulut, Ü., S. Sarıdemir, U. Rajak, F. Polat, A. Afzal, T.N. Verma, 2021. Effects of high-dosage copper oxide nanoparticles addition in diesel fuel on engine characteristics. Energy, **229**: pp. 120611 doi: 10.1016/j.energy.2021.120611.

[43] Ağbulut, Ü., M. Karagöz, S. Sarıdemir, A. Öztürk, 2020. Impact of various metal-oxide based nanoparticles and biodiesel blends on the combustion, performance, emission, vibration and noise characteristics of a CI engine. Fuel, **270**: pp. 117521 doi: 10.1016/j.fuel.2020.117521.

[44] Roy, R.G., Ü. Ağbulut, C.P. Koshy, Y. Alex, K. Sailesh, S.A. Khan, R. Jilte, E. Linul, M. Asif, 2024. Impact of synthesizing surfactant-modified catalytic ceria nanoparticles on the performance and environmental behaviors of coconut oil/diesel-fueled CI engine: An optimization attempt. Energy, **295**: pp. 130825 doi: 10.1016/j.energy.2024.130825.

[45] Karagoz, M., C. Uysal, U. Agbulut, S. Saridemir, 2021. Exergetic and exergoeconomic analyses of a CI engine fueled with diesel-biodiesel blends containing various metal-oxide

nanoparticles. Energy, **214**: pp. 118830 doi: 10.1016/j.energy.2020.118830.

[46] Siddartha, G.N.V., C.S. Ramakrishna, P.K. Kujur, Y.A. Rao, N. Dalela, A.S. Yadav, A. Sharma, 2022. Effect of fuel additives on internal combustion engine performance and emissions. Materials Today: Proceedings, **63**: pp. A9-A14 doi: 10.1016/j.matpr.2022.06.307.

[47] Hoang, A.T., M.X. Le, S. Nižetić, Z. Huang, Ü. Ağbulut, I. Veza, Z. Said, A.T. Le, V.D. Tran, X.P. Nguyen, 2022. Understanding behaviors of compression ignition engine running on metal nanoparticle additives-included fuels: a control comparison between biodiesel and diesel fuel. Fuel, **326**: pp. 124981 doi: 10.1016/j.fuel.2022.124981.

[48] Spikes, H., 2015. Friction modifier additives. Tribology Letters, **60**: pp. 1-26 doi: 10.1007/s11249-015-0589-z.

[49] Youssef, A.,A. Ibrahim, 2024. An experimental evaluation for the performance of a single cylinder CI engine fueled by a Diesel-Biodiesel blend with alcohols and Zinc-Aluminate nanoparticles as additives. Materials Today: Proceedings, doi: 10.1016/j.matpr.2024.04.015.

[50] Yuvarajan, D., M.D. Babu, N. BeemKumar, P.A. Kishore, 2018. Experimental investigation on the influence of titanium dioxide nanofluid on emission pattern of biodiesel in a diesel engine. Atmospheric Pollution Research, **9**(1): pp. 47-52

[51] Prabakaran, B.,A. Udhoji, 2016. Experimental investigation into effects of addition of zinc oxide on performance, combustion and emission characteristics of diesel-biodiesel-ethanol blends in CI engine. Alexandria Engineering Journal, **55**(4): pp. 3355-3362 doi: 10.1016/j.aej.2016.08.022.

[52] Prabu, A., 2018. Nanoparticles as additive in biodiesel on the working characteristics of a DI diesel engine. Ain shams Engineering journal, **9**(4): pp. 2343-2349 doi: 10.1016/j.asej.2017.04.004.

[53] Sajith, V., C. Sobhan, G. Peterson, 2010. Experimental investigations on the effects of cerium oxide nanoparticle fuel additives on biodiesel. Advances in Mechanical Engineering, **2**: pp. 581407 doi: 10.1155/2010/581407.

[54] Chandrasekaran, V., M. Arthanarisamy, P. Nachiappan, S. Dhanakotti, B. Moorthy, 2016. The role of nano additives for biodiesel and diesel blended transportation fuels. Transportation Research Part D: Transport and Environment, **46**: pp. 145-156 doi: 10.1016/j.trd.2016.03.015.

[55] Jayanthi, P.,M.S. Rao, 2016. Effects of nanoparticles additives on performance and emissions characteristics of a DI diesel engine fuelled with biodiesel. International Journal of Advances in Engineering & Technology, **9**(6): pp. 689 doi: 10.7323/ijaet/v9_iss6.

[56] Annamalai, M., B. Dhinesh, K. Nanthagopal, P. SivaramaKrishnan, J.I.J. Lalvani, M. Parthasarathy, K. Annamalai, 2016. An assessment on performance, combustion and emission behavior of a diesel engine powered by ceria nanoparticle blended emulsified biofuel. Energy conversion and management, **123**: pp. 372-380 doi: 10.1016/j.enconman.2016.06.062.

[57] Devarajan, Y., D.B. Munuswamy, A. Mahalingam, 2017. Performance, combustion and emission analysis on the effect of ferrofluid on neat biodiesel. Process Safety and Environmental Protection, **111**: pp. 283-291 doi: 10.1016/j.psep.2017.07.021.

[58] Shaafi, T.,R. Velraj, 2015. Influence of alumina nanoparticles, ethanol and isopropanol blend as additive with diesel–soybean biodiesel blend fuel: Combustion, engine performance and emissions. Renewable Energy, **80**: pp. 655-663 doi: 10.1016/j.renene.2015.02.042.

[59] Özgür, T., M. Özcanli, K. Aydin, 2015. Investigation of nanoparticle additives to biodiesel for improvement of the performance and exhaust emissions in a compression ignition engine. International journal of green energy, **12**(1): pp. 51-56 doi: 10.1080/15435075.2014.889011.

[60] Aalam, C.S., C. Saravanan, M. Kannan, 2015. Experimental investigations on a CRDI system assisted diesel engine fuelled with aluminium oxide nanoparticles blended biodiesel. Alexandria engineering journal, **54**(3): pp. 351-358 doi: 10.1016/j.aej.2015.04.009.

[61] Sadhik Basha, J.,R. Anand, 2013. The influence of nano additive blended biodiesel fuels on the working characteristics of a diesel engine. Journal of the Brazilian Society of Mechanical Sciences and Engineering, **35**: pp. 257-264 doi: 10.1007/s40430-013-0023-0.

[62] Gürü, M., U. Karakaya, D. Altıparmak, A. Alıcılar, 2002. Improvement of diesel fuel properties by using additives. Energy conversion and Management, **43**(8): pp. 1021-1025 doi: 10.1016/S0196-8904(01)00094-2.

[63] Vellaiyan, S.,C.A. Partheeban, 2020. Combined effect of water emulsion and ZnO nanoparticle on emissions pattern of soybean biodiesel fuelled diesel engine.

Renewable Energy, **149**: pp. 1157-1166 doi: 10.1016/j.renene.2019.10.101.

[64] Choi, Y., C. Lee, Y. Hwang, M. Park, J. Lee, C. Choi, M. Jung, 2009. Tribological behavior of copper nanoparticles as additives in oil. Current Applied Physics, **9**(2, Supplement): pp. e124-e127 doi: 10.1016/j.cap.2008.12.050.

[65] Mortier, R.M., S.T. Orszulik, M.F. Fox, 2010. Chemistry and technology of lubricants. Vol. 107115. Springer. doi: 10.1007/978-1-4020-8662-5.

[66] Barnes, A.M., K.D. Bartle, V.R.A. Thibon, 2001. A review of zinc dialkyldithiophosphates (ZDDPS): characterisation and role in the lubricating oil. Tribology International, **34**(6): pp. 389-395 doi: 10.1016/S0301-679X(01)00028-7.

[67] Rudnick, L.R., 2009. Lubricant additives: chemistry and applications. CRC press. doi: 10.1201/9781420059656.

[68] Bakunin, V., A.Y. Suslov, G. Kuzmina, O. Parenago, A. Topchiev, 2004. Synthesis and application of inorganic nanoparticles as lubricant components–a review. Journal of Nanoparticle Research, **6**: pp. 273-284 doi: 10.1023/B:NANO.0000034720.79452.e3.

[69] Li, X., Z. Cao, Z. Zhang, H. Dang, 2006. Surface-modification in situ of nano-SiO2 and its structure and tribological properties. Applied Surface Science, **252**(22): pp. 7856-7861 doi: 10.1016/j.apsusc.2005.09.068.

[70] Battez, A.H., R. González, J. Viesca, J. Fernández, J.D. Fernández, A. Machado, R. Chou, J. Riba, 2008. CuO, ZrO2 and ZnO nanoparticles as antiwear additive in oil lubricants. Wear, **265**(3-4): pp. 422-428 doi: 10.1016/j.wear.2007.11.013.

[71] Cellard, A., V. Garnier, G. Fantozzi, G. Baret, P. Fort, 2009. Wear resistance of chromium oxide nanostructured coatings. Ceramics International, **35**(2): pp. 913-916 doi: 10.1016/j.ceramint.2008.02.022.

[72] Hwang, Y., C. Lee, Y. Choi, S. Cheong, D. Kim, K. Lee, J. Lee, S.H. Kim, 2011. Effect of the size and morphology of particles dispersed in nano-oil on friction performance between rotating discs. Journal of Mechanical Science and Technology, **25**(11): pp. 2853-2857 doi: 10.1007/s12206-011-0724-1.

[73] Ali, Z.A.A.A., A.M. Takhakh, M. Al-Waily, 2022. A review of use of nanoparticle additives in lubricants to improve its tribological properties. Materials Today: Proceedings, **52**: pp. 1442-1450 doi: 10.1016/j.matpr.2021.11.193.

[74] Waqas, M., R. Zahid, M.U. Bhutta, Z.A. Khan, A. Saeed, 2021. A review of friction performance of lubricants with nano additives. Materials, **14**(21): pp. 6310 doi: 10.3390/ma14216310

[75] Shahnazar, S., S. Bagheri, S.B. Abd Hamid, 2016. Enhancing lubricant properties by nanoparticle additives. International journal of hydrogen energy, **41**(4): pp. 3153-3170 doi: 10.1016/j.ijhydene.2015.12.040.

[76] Srivyas, P.,M. Charoo, 2018. A Review on Tribological Characterization of Lubricants with Nano Additives for Automotive Applications. Tribology in Industry, **40**(4) doi: 10.24874/ti.2018.40.04.08.

[77] Wu, Y.Y., W.C. Tsui, T.C. Liu, 2007. Experimental analysis of tribological properties of lubricating oils with nanoparticle additives. Wear, **262**(7): pp. 819-825 doi: 10.1016/j.wear.2006.08.021.

[78] Mangam, V., S. Bhattacharya, K. Das, S. Das, 2010. Friction and wear behavior of Cu–CeO2 nanocomposite coatings synthesized by pulsed electrodeposition. Surface and Coatings Technology, **205**(3): pp. 801-805 doi: 10.1016/j.surfcoat.2010.07.119.

[79] Jiao, D., S. Zheng, Y. Wang, R. Guan, B. Cao, 2011. The tribology properties of alumina/silica composite nanoparticles as lubricant additives. Applied Surface Science, **257**(13): pp. 5720-5725 doi: 10.1016/j.apsusc.2011.01.084.

[80] Battez, A.H., J. Viesca, R. González, D. Blanco, E. Asedegbega, A. Osorio, 2010. Friction reduction properties of a CuO nanolubricant used as lubricant for a NiCrBSi coating. Wear, **268**(1-2): pp. 325-328 doi: 10.1016/j.wear.2009.08.018.

[81] Song, X., S. Zheng, J. Zhang, W. Li, Q. Chen, B. Cao, 2012. Synthesis of monodispersed ZnAl2O4 nanoparticles and their tribology properties as lubricant additives. Materials Research Bulletin, **47**(12): pp. 4305-4310 doi: 10.1016/j.materresbull.2012.09.013.

[82] Shi, G., M.Q. Zhang, M.Z. Rong, B. Wetzel, K. Friedrich, 2004. Sliding wear behavior of epoxy containing nano-Al2O3 particles with different pretreatments. Wear, **256**(11): pp. 1072-1081 doi: 10.1016/S0043-1648(03)00533-7.

[83] Kirloskar Oil Engines Limited. 2024 05-05-2024]; Available from: https://www.kirloskaroilengines.com/.

[84] Castrol GTX Diesel 15W-40. October 2023 05-05-2024]; Available from: https://msdspds.castrol.com/msdspds/msdspds.nsf/CastrolResults?OpenForm&c=India%20(IN)&l=English%20(GB)&p=GTX%20DIESEL%2015W-40&n=&b=All&t=PDS&autosearch=No&autoload=No&sitelang=EN&output=Full&spu=Lubricants&unrestrictedmb=No&cols=0& g

a=2.262209164.1659088950.1714848024-1839148607.1714848024.

[85] BANDELIN electronic GmbH & Co. KG Germany. [cited 2024 17th May]; Available from: https://bandelin.com/en/shop/sonorex-digitec-ultrasonic-bathrooms/sonorex-digitec-dt-514-h/.

[86] ASTM, D 446 : Standard Speci®cations and Operating Instructions for Glass Capillary Kinematic Viscometers. 1999, ASTM, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959, United States.